

# LCA case study. Part 1: cradle-to-grave environmental footprint analysis of composites and stainless steel I-beams

Suphunnika Ibbotson · Sami Kara

Received: 29 November 2011 / Accepted: 28 May 2012 / Published online: 13 June 2012  
© Springer-Verlag 2012

## Abstract

**Purpose** I-beams for outdoor structures are traditionally made from conventional materials such as stainless steel due to its high strength and corrosive resistant properties. Alternatively, the I-beam can also be made from composite materials such as glass-reinforced plastics (GRP), which provide similar properties under a lighter weight and a lower cost condition. Nonetheless, their environmental footprint performance depends largely on activities involved during their life cycle. Therefore, the findings are presented in two parts: Part 1 and 2. This paper is about Part 1, which presents the environmental footprint for the cradle-to-grave of one linear metre I-beam that is made from two materials namely stainless steel (316) and GRP. Part 2, which will be submitted as a separate paper, has specifically analysed their environmental and economic impacts for the different cradle-to-gate scenarios and the potential carbon tax.

**Materials and methods** Materials that were used to compare the environmental footprint of an I-beam are GRP and stainless steel (316). Their cradle-to-grave activities included raw material extraction, supplier transportation, manufacturing process, distribution, disposal transportation and process. Input data were based on data provided by a composites company in Australia, the Ecoinvent 2.2 and Australian data 2007 databases. The World ReCiPe midpoint

and endpoint methods were used to assess the environmental footprint.

**Results and discussion** The environmental footprint results for the cradle-to-grave of the I-beams are presented as a contribution percentage of the single score unit in the total and damage category levels which produced by the endpoint method. The characteristic and normalisation results were also generated for all impact categories by the midpoint method.

**Conclusions** Overall, the cradle-to-grave results show that the composite I-beam produces 20 % less environmental footprint than that of the stainless steel I-beam. The human health damage category is affected the most due to the main contribution from the material stage. The cradle-to-gate results are contributed by 90 % from raw material extraction, 7 % from the manufacturing process and 3 % from the supplier transportation. In terms of the characteristic results, the composite I-beam produces less environmental impact in most of the impact categories except for the climate change, photochemical oxidant formation, terrestrial acidification, marine eutrophication, natural land transformation and fossil depletion. Therefore, the influential parameters of these impact categories are investigated further in Part 2 where the environmental footprint and economic impact are estimated for different cradle-to-gate scenarios of the I-beams.

Responsible editor: Holger Wallbaum

Continuation of research presented in the 7th Australian Conference on Life Cycle Assessment Melbourne, March 2011.

S. Ibbotson (✉) · S. Kara  
Life Cycle Engineering and Management Research Group, School  
of Mechanical and Manufacturing Engineering,  
The University of New South Wales,  
Sydney, NSW, Australia 2052  
e-mail: suphunnika@unsw.edu.au

**Keywords** Cradle-to-grave · Composites · Construction · Environmental footprint · ReCiPe

## Abbreviations

LCA Life Cycle Assessment  
LCI Life Cycle Inventory  
LCIA Life Cycle Impact Assessment  
GRP Glass reinforced plastics

I	Moment of inertia
IEA	International Energy Agency
CFC	Chlorofluorocarbon
Fe	Iron

## 1 Introduction

As the world population is exponentially growing, the demand of building constructions is likely to increase in order to support human needs for shelters and infrastructure. The constructions must be designed by an architect and a structural engineer to satisfy customer specification, safety requirements under a cost-effective budget (Hansen and Zenobia 2011). These design criteria are highly associated with the amount of materials used during building of the construction and the energy consumed during the building's service life.

Large quantities of building materials such as universal beams, columns, battens and fasteners are often utilised to build a good foundation for supporting the entire structure of the construction. Their bill of materials and costs for those beams are calculated based on the beam load capacity, stress and deflection (Simites and Hodges 2005). After the building was constructed, energy and materials continue to be consumed during its service life either directly by supporting facilities (e.g. air conditioning and lighting systems) or by maintenance activities (e.g. painting or replacement) (Ramesh et al. 2010).

Traditionally, building constructions must consider those prescribed design criteria where they tend to ignore the environmental impact associated with the entire life cycle of the building construction. However, an environmental requirement has been considered as an additional design criterion for the past decades (Lawson 1996) due to the rising concerns of natural disasters, pollutions and resource scarcities. Therefore, a green building concept was established to manage the resource efficiency of a building construction to consider both economic and environmental impacts (Ortiz et al. 2009).

Generally, a life cycle of construction building consumes 80–90 % of their total energy consumption during its operating hours, while 10–20 % of the energy is embodied energy in the building materials (Ramesh et al. 2010). The environmental footprint of the latter can be improved by increasing the energy efficiency of the supporting systems such as ventilation, water heating and lighting systems. Whereas in the building materials case, their associated environmental impact is fixed and cannot be reduced once they are built. Therefore, a number of studies have focused on analysing the environmental footprint associated with different building

materials (Bribián et al. 2011; Khasreen et al. 2009; Ortiz et al. 2009; Ramesh et al. 2010; Torgal and Jalali 2011). These studies often used Life Cycle Assessment (LCA) to assess the environmental footprint for four product life cycle stages namely materials, manufacturing process, usage and end-of-life (Sharma et al. 2011). The scope of the assessment can be defined based on the cradle-to-gate which considers the first two stages and the cradle-to-grave that covers all stages (Bribián et al. 2009). For instance, Bribián et al. (2011) analysed both energy and environmental impacts of building materials including steel, wood, cements and concrete. Kosareo and Ries (2007) conducted the environmental assessment for a life cycle of a green roof. Tarantini et al. (2011) studied the green public procurement using the life cycle approach and tested with a window case study which compared aluminium and PVC window frames. Torgal and Jalali (2011) emphasised on the eco-efficiency for different constructions and building materials.

Amongst those structural materials, I-beams are also used in a large quantity to withstand the weight and the forces of the entire construction. Other properties (e.g. corrosion resistance and coating surface) are also additionally required for the application of an outdoor structure such as walkways and shelters. For this kind of application, an I-beam is traditionally made from conventional materials such as stainless steel due to its high strength and corrosive resistance (Ashby 2009). These days, it can also be made from alternative materials such as composites that provide an equivalent strength and corrosive resistance with considerably lower weight and material cost (Ashby 2009). Nonetheless, their environmental footprint performance is largely dependent on activities involved during their product life cycle stages (Bribián et al. 2011; Kara et al. 2010; Kosareo and Ries 2007; Nebel et al. 2006; Basbagill et al. 2012; Song et al. 2009; O'Brien-Bernini 2011; Rajendran et al. 2012; Mayyas et al. 2012; Simões et al. 2012; La Mantia and Morreale 2011; Ortiz et al. 2010; Dittenber and GangaRao 2011).

For example, Song et al. analysed the life cycle energy of fibre-reinforced composites by comparing composite vehicle to steel and aluminium vehicles (Song et al. 2009). They found that composite structures save more energy than steel but not aluminium. Rajendran et al. found that the environmental advantages in terms of the resource depletion and global warming when using recycled plastics instead of virgin plastics in making a composite car part, are closely associated with the collecting and recycling processes involved in the plastic waste feed stock (Rajendran et al. 2012). Basbagill et al. investigated the human health impact of resin mix, concentration levels and workplace inhalation toxicity exposure levels for the North American pultrusion

factories. The survey and LCA were conducted LCA for three different resin mixes of fibre-reinforced polymer composite materials. The results revealed that the material has low environmental impacts particularly for the carcinogen, respiratory organics and inorganics impact categories (Basbagill et al. 2012). This is because the activities such as raw material extraction, manufacturing process, transportation and disposal processes consume certain resources (e.g. materials, fuels and energy) and release emissions and wastes.

Therefore, this research aims to thoroughly investigate the environmental footprint of one linear metre I-beam that is made from two materials namely stainless steel (316) and glass-reinforced plastics (GRP). This publication is Part 1 of the research that assesses the screening LCA for the cradle-to-grave of a linear metre I-beam that is made from the two building materials. Part 2 of this research, which will be a separate paper, will continue to analyse the environmental footprint, economic impact and the potential carbon tax of their cradle-and gate and different supply chain scenarios. This paper presents the methodology in the next section by following the four steps of LCA; subsequently results are discussed in the later section.

## 2 Life cycle assessment

Environmental footprint of a linear metre I-beam was assessed using the screening LCA. The analysis was conducted through the four basic steps outlined in ISO 14040s (ISO14040 2006). The steps include (1) goal and scope definition, (2) Life Cycle Inventory (LCI) analysis, (3) Life Cycle Impact Assessment and (4) interpretation. The four steps are presented as follows.

### 2.1 LCA goal and scope

According to the background section, this research is interested in demonstrating the environmental footprint of the cradle-to-grave for a linear metre I-beam that is made from composites and stainless steel (316). The composite material in this case is the GRP. The research aims to compare the environmental performance of the traditional and alternative materials across their materials, manufacturing process, usage and end-of-life stages.

Generally, the two comparable I-beams are required to have an equivalent flexural stiffness to withstand the same structural weight and forces. They will be constructed with the same amount of supporting components such as fasteners. Therefore, the functional unit is a cradle-to-grave of a linear metre I-beam made from GRP and stainless steel (316) that has the same equivalent flexural stiffness as given in Eq. 1.  $E_f$  represents the flexural modulus in a unit of

megapascal and  $I$  is the second moment of Inertia in a unit of quartic millimetre ( $\text{mm}^4$ ).

$$E_{f_{\text{stainless steel}}} I_{\text{stainless steel}} = E_{f_{\text{composite}}} I_{\text{composite}} \quad (1)$$

According to this equation, the weight of the composite I-beam was given by the company as 3.28 kg per linear metre, hence the weight of the stainless steel (316) I-beam was derived from the given weight as 3.93 kg per linear metre. This derivative weight was calculated based on the fact that the composite I-beam has the flexural modulus ( $E_{f_{\text{composite}}}$ ) of 13,800 MPa and the second moment of inertia ( $I_{\text{composite}}$ ) of 6,234,800  $\text{mm}^4$ . Subsequently, a dimension of the stainless steel I-beam was derived from the second moment of inertia ( $I_{\text{stainless steel}}$ ) of 463,769  $\text{mm}^4$  as  $76.67 \times 38.1 \times 3.41$  mm.

The system boundaries of these linear metre I-beams are depicted in Figs. 1 and 2. In this case, the boundaries cover the raw materials, emissions and wastes of the raw material extraction process, associated transportation of sourcing materials, manufacturing processes, distribution and disposal transportation as well as disposal processes. The raw materials are extracted and processed in four overseas countries and Australia, which are then transported to the manufacturing plant in Australia by road and water transportation. The manufacturing processes of the stainless steel I-beam involve the stainless steel production and the hot rolling processes.

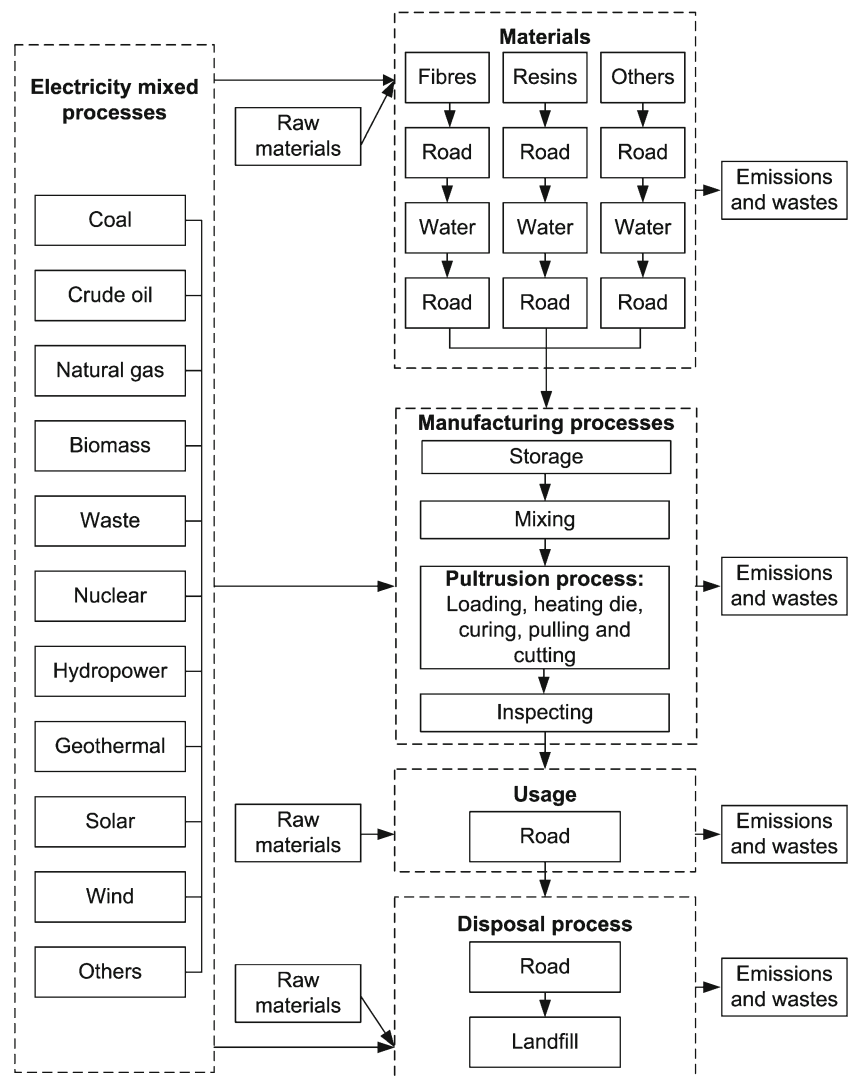
The composite I-beam is manufactured largely by the pultrusion process. The assumed distribution is also considered as road transportation for the usage stage of both I-beams. Other activities such as their installation and maintenance were excluded as they were assumed to use the same quantities of materials and energy during their equalled service lifetime. The disposal stage of the I-beams was also assumed to include road transportation from the customer to the disposal site as well as the recycling and landfill processes.

### 2.2 Life cycle inventory

According to the system boundaries, LCI was mainly based on the input data in Table 1 provided by the composite company and the two main LCI libraries are the Ecoinvent 2.2 (Ecoinvent Centre 2010) and the Australian data 2007 databases (Grant 2010). The LCI databases provide the raw materials, emissions and wastes as presented in Figs. 1 and 2. The stainless steel I-beam was based on the Ecoinvent 2.2 database, which approximately based on 60 % and 40 % of the primary and secondary materials, respectively.

The GRP I-beam is made from 14 raw materials that are manufactured by Australians and four overseas suppliers as indicated in Table 1. These suppliers have distinctive

**Fig. 1** System boundary of the cradle-to-grave for a linear metre of the composite I-beam

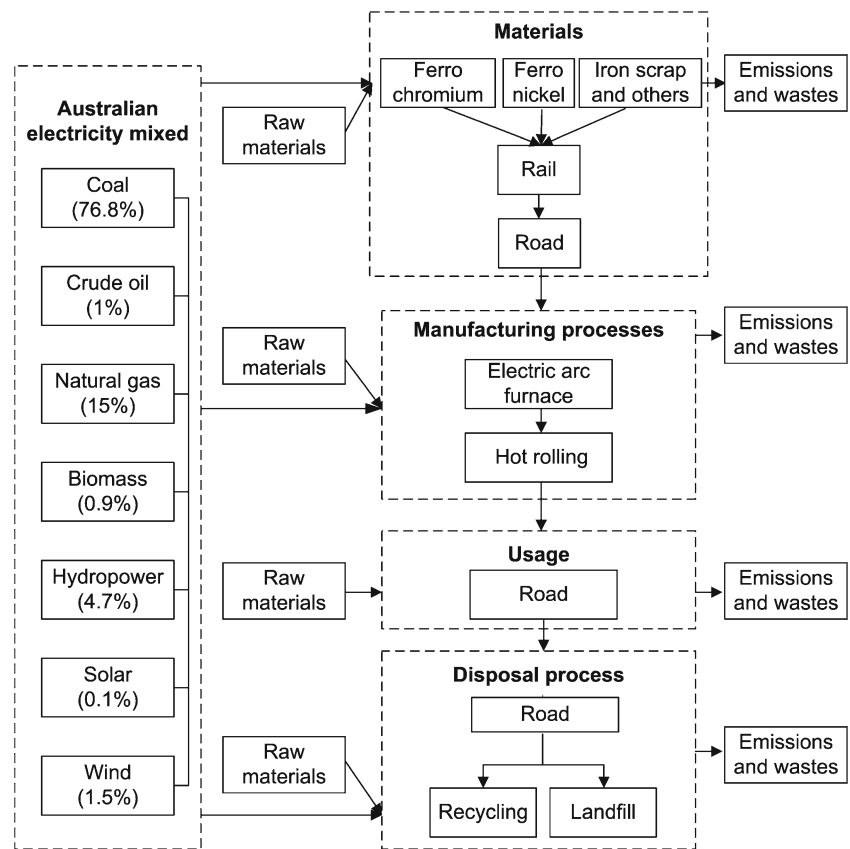


characteristics. Australian suppliers offer the fastest delivery via road transportation at a relatively high price. The USA supplier offers specific raw materials at a slightly lower price than the Australian suppliers with a moderate travel distance using long road and water transportation and another short road transportation. For those three Asian suppliers, Asia 1 represents the supplier that offers raw material with the lowest cost and involves moderate travel distance. Asia 3 is the supplier that provides higher priced raw materials at the shortest travel distance. Asia 2 delivers raw materials at a moderate price and uses a high combination of the transportation modes since it involves the longest travel distance. The transportation modes and travel distances for delivering the raw materials of the two I-beams were based on the company data and the estimation from the online Google map (Google Map 2012) and the Portworld (Portworld 2012) website.

The raw materials comprise glass fibre, plastic resins and chemicals that deliver from the suppliers to the manufacturing plant in Australia via road and water transportation. The

quantities of raw materials were also taken into account the waste produced during the manufacturing process. The stainless steel of the other I-beam was assumed to be sourced within Australia and delivered to the manufacturing plant by road transportation. Noticeably, these raw materials are manufactured in certain countries that have no electricity mix process cases in the Ecoinvent 2.2 database. Therefore, for a consistency of the analysis, certain modifications were made to accommodate different combinations of energy sources for electricity used in those five countries. The electricity mix for those countries in Figs. 1 and 2 were modified on a basis of the data published by (1) the Chinese electricity mix process case of the Ecoinvent 2.2 database; (2) the ‘electricity/heat’ data from International Energy Agency (IEA) in 2008 (International Energy Agency 2008) and (3) IEA’s CO<sub>2</sub> emission report (International Energy Agency 2010). These two IEA data were chosen as they provide generic quantitative data for the electricity production and its CO<sub>2</sub> emissions associated with those countries.

**Fig. 2** System boundary of the cradle-to-grave for a linear metre of the stainless steel I-beam



The new electricity mix case was modelled by replacing the output in kilowatt-hour and the technosphere inputs of the Chinese electricity mix process case with the data reported in the electricity data of IEA in 2008 (International Energy Agency 2008). The data included the ‘total production’ and the amount of electricity production from various energy sources namely coal, oil, gas, biomass, waste, nuclear, hydropower, geothermal, solar, wind and other sources. The Chinese electricity mix process case was chosen

amongst the Chinese and the USA, US ‘electricity mix’ process cases from the Ecoinvent 2.2 database due to two main reasons. First, it uses coal as the main energy source which is similar to the Australian electricity situation. Second, its modified electricity mix processes give a similar CO<sub>2</sub> emission trend as assessed by SimaPro 7.3 when compared to the CO<sub>2</sub> emissions in grams per kilowatt-hour trend reported in the IEA CO<sub>2</sub> emission report. According to the report, the Australian electricity mix has the highest value

**Table 1** Input data for the cradle-to-grave of the I-beams

Cradle-to-grave	Description	Composite I-beam	Stainless steel (316) I-beam
Material <sup>a</sup>	Weight per 1 m	3.28 kg	3.93 kg
	Suppliers	Australian, Asia1, Asia2, Asia3 and USA	Australian
Manufacturing process <sup>a</sup>	Transportation	Trucks and ships	Trucks
	Forming process for 1 linear metre I-beam	Pultrusion process	Hot rolling process
Usage <sup>b</sup>	Distribution	Truck, travel distance of 100 km	
End-of-life	Disposal transportation and process	- Truck, travel distance of 200 km <sup>b</sup>	- Truck, travel distance of 100 km <sup>b</sup>
		- 100 % landfill <sup>a</sup>	- 70 % recycling <sup>c</sup> - 30 % landfill <sup>c</sup>

<sup>a</sup> Company provided data

<sup>b</sup> Arbitrarily assumption

<sup>c</sup> Australian 2007 data (LCI database)

followed by Asia 1, Asia 3, USA and Asia 2 electricity mix processes (International Energy Agency 2010).

Thereafter, the modelled Australian electricity mix was also used for the manufacturing process stage of both I-beams as they are fabricated in Australia. A combination of the energy sources used for the Australian electricity mix is presented in Fig. 2 (International Energy Agency 2008). In the case of the pultrusion process in Fig. 1, the modelled Australian electricity mix was used as LCI for representing the electricity used by such process and its supporting system. The quantity of the electricity consumption was estimated from the company production and energy accounting data which were then converted into the production of one linear metre composite I-beam. Thus, the electricity consumption in Fig. 1 was broken down into the energy consumption for the manufacturing processes involved including the pultrusion process. This process involves: pulling fibreglass through a mixture of resins and chemicals; curing this mixed component in a heated die; and cutting it into a desired length. Likewise, LCI of the stainless steel I-beam in Fig. 2 also adapted the modelled Australian electricity mix into the electricity consumed by the stainless steel production and the hot rolling process cases of the Ecoinvent 2.2 database (Ecoinvent Centre 2010).

The usage condition for both I-beams was assumed to be the same in this research. This means that the application of the composite I-beam was assumed to be used in a similar manner to the stainless steel I-beam. For instance, both I-beams are used in the same quantities and require an equalled numbers of fasteners. They are required to be replaced at the same period of service life.

Therefore, distribution transportation was the only activity that considered in this usage stage as shown in Figs. 1 and 2, and they were arbitrarily assumed as 100 km. The end-of-life stage of both I-beams was assumed to be transported to a disposal site with an arbitrary distance of 200 km. The disposal process assumed for the stainless steel I-beam in Fig. 2 are 70 % recycling and 30 % landfill, while 100 % landfill in Fig. 1 was assumed for the composite I-beam by the company.

These disposal assumptions were based on the ‘Household waste’ process case from the Australian data 2007 database (Grant 2010). The recycling process of the database was based on an average Australian household behaviour that separates their wastes such as glass, paper and plastics which are collected by the municipality. Road transportation was included in this recycling model for transferring the wastes to the recycling site. Then, the reprocessing steel uses inputs as raw materials such as water and caustic soda, and the outputs of this recycling process are the recycled steel and waste as shredder dust. The recycling efficiency was assumed as 95 %.

### 2.3 Impact assessment

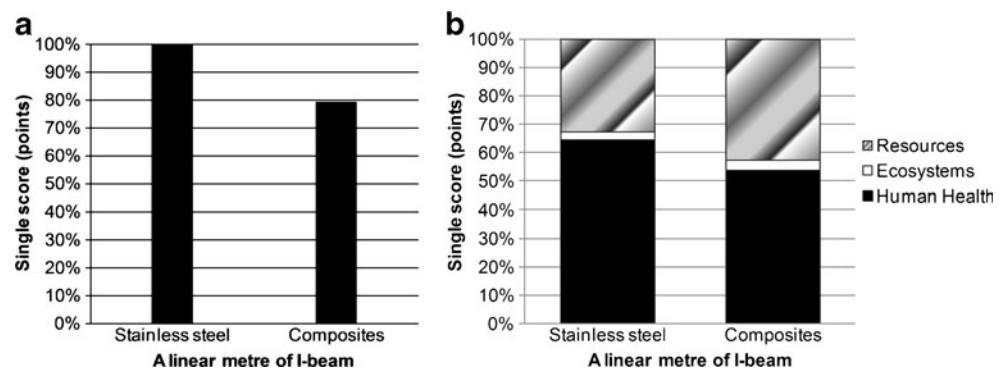
The life cycle impact assessment step was carried out using the World ReCiPe midpoint and endpoint H/A methods from SimaPro 7.3 software. The methods were developed in 2008 by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft (Goedkoop et al. 2009). These methods were chosen to assess the environmental footprint that considers the human health, ecosystem and resources in a global scale. Various LCA studies have employed such methods in many applications (Prasara and Grant 2011; Belboom et al. 2011; Jones and McManus 2010). The midpoint method provides lower uncertainty results, while the endpoint method offers the results which are easily to communicate with an end-user (Recipe 2011). The midpoint method provides the characteristic results for different impact categories in distinctive units and the normalisation results in a dimensionless unit. The endpoint method gives the damage categories and single score in a points unit. Hence, the impact assessment results of the screening LCA are presented in the next section.

### 3 Results

Figure 3a shows the total environmental footprint results of the cradle-to-grave for both I-beams. As it can be seen, the one linear metre of composite I-beam produces 20 % less environmental impacts than that of the stainless steel I-beam. In particular, approximately 64 % of the stainless steel I-beam in Fig. 3b is contributed by the human health damage category which causes toxics produced by extracting its raw materials, ferrous minerals such as ferronickel and ferrochromium. The other contributions belong to 33 % and 3 % of the resources and the ecosystems damage categories. However, the contributions of the damage category results for the composite I-beam are slightly different. In this case, the approximations of the human health and the resources damage categories are 54 % and 43 % respectively, while the rest belongs to the ecosystem damage category. The reason being that composites comprise many raw materials including plastic resins and chemicals. These raw materials consume significant amount of resources and electricity, and also release wastes and emissions during their production process.

Figure 4a highlights the environmental footprint contributed in each product life cycle. Clearly, the material stage is the hot spots of the cradle-to-grave results as they contribute more than 90 %. At this stage, the stainless steel I-beam has a higher contribution than the composite I-beam. This is predominantly owing to the steel production and the electric arc furnace processes that produce relatively higher amount of emissions compared to the composites production. The

**Fig. 3** Contribution percentage of **a** the single score and **b** the damage category results for the life cycles of the linear metre stainless steel and the composite I-beams



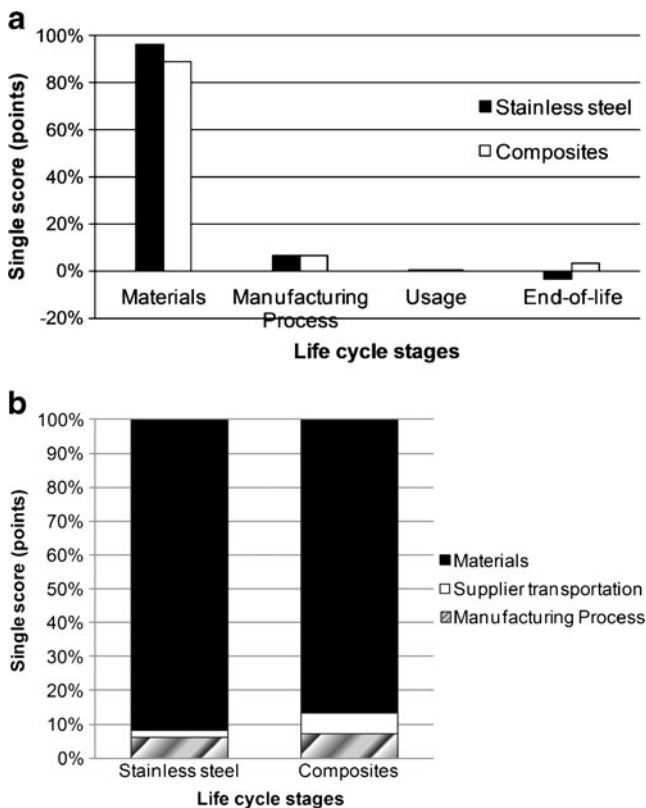
manufacturing process stage of the I-beams produces approximately 7 % and the end-of-life of the stainless steel gains the benefits from the recycling process by -3 % (the negative value indicates the benefits gained). These two stages reveal that the composite I-beam has a higher contribution than that of the stainless steel I-beam. This is mainly due to different scope of the electricity consumed by the manufacturing processes which can vary the environmental footprint values. On this token, the hot rolling process of the stainless steel I-beam from the Ecoinvent database considers mainly the electricity consumed by the process. Whereas, the composite I-beam company data includes the electricity

consumption of the manufacturing processes as well as the supporting facilities.

The cradle-to-gate of the I-beam is analysed further in Fig. 4b. The figure reveals that the raw material extraction of the stainless steel I-beam produces more than 90 % of the cradle-to-gate. The contribution of the composite I-beam is approximately 87 % because nearly 10 % of the environmental footprint of the composite I-beam is caused by the associated transportation. The transportation associated with the cradle-to-gate assessment of the I-beams was carried out by the road transportation (the 'Transport, lorry >16 t, fleet average/RER U') and the water transportation (the 'Transport, transoceanic freight ship/OCE U') from the Ecoinvent 2.2 database. Their assumed travel distances were modified from the company data which ranged from 150 to 4,500 km and 11,000 to 18,000 km, respectively. Therefore, the higher contribution of these transportation modes are substantially affected by fuel consumed during transferring those 14 raw materials from suppliers to the manufacturing plant.

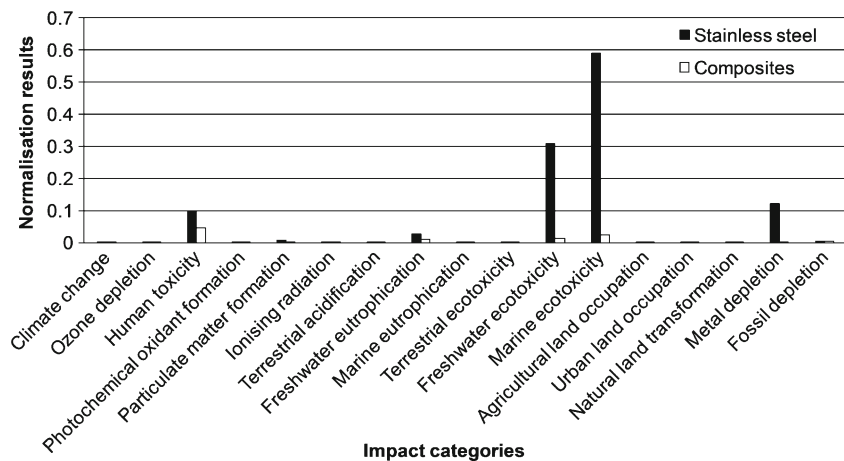
The influence of the cradle-to-gate can be elaborated further in Figs. 5 and 6 by respectively viewing the normalisation and the characteristic results for the cradle-to-grave of the I-beams. In terms of the normalisation results, Fig. 5 shows that significant reduction of the environmental footprint in all impact categories when using the composite I-beam in lieu of the stainless steel I-beam. However, Fig. 6 reveals a slightly different trend for the characteristic results where each individual impact category is represented under their own unit such as kilogramme CO<sub>2eq</sub>, kilogramme CFC<sub>eq</sub> and kilogramme Fe<sub>eq</sub> (Recipe 2011). The composite I-beam produces less environmental footprint than the stainless steel I-beam in most impact categories. This particularly applies for the metal depletion and the water related ecotoxicity impact categories due to the production and the emissions of involved metals such as ferrochromium, ferronickel and iron.

On the contrary, certain impact categories of the composite I-beam have almost equal or slightly higher environmental footprint than that of the stainless steel I-beam. These impact categories are the climate change, photochemical oxidant formation, terrestrial acidification, marine eutrophication,



**Fig. 4** Contribution percentage of **a** the cradle-to-grave and **b** the cradle-to-gate for a linear metre of the stainless steel and the composite I-beams

**Fig. 5** Normalisation results for the cradle-to-grave of the linear metre stainless steel and the composite I-beams



natural land transformation and fossil depletion. Such drawbacks of the composite I-beam are predominantly caused by the cradle-to-gate activities. Further investigation of the cradle-to-gate will be presented in a separate publication, Part 2, to demonstrate on how to improve these shortcomings by altering supply chain situations.

#### 4 Uncertainty and limitations

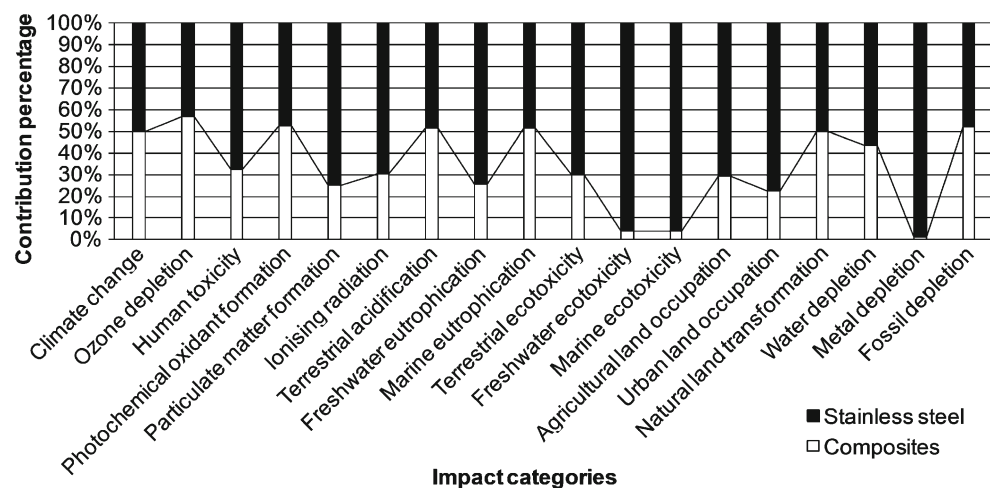
Most of the input data used in this research were sourced primarily from readily data available in the composite manufacturer such as the Material Safety Datasheets (MSDs) and utility bills. Additional assumptions were made due to the limitation of the input data obtained from these data sources. Other uncertainties may also incur from the LCI databases as they developed from either primary or secondary databases (e.g. company data, literature or extrapolation) for a generic process which has certain database background such as timeframe and technology level. The environmental footprint of the I-beams may vary due to these assumptions and uncertainties hence a break-even and a sensitivity

analysis were conducted to assess their impacts towards the assessment results. Their impacts are highlighted as follows.

Firstly, the analysis assumed that all chemicals used in making the composite I-beam were made from the ‘chemical inorganic’ process case which is based on a combination of processes used by common chemicals. MSDs of chemicals often excluded the ingredient data of the raw materials hence this process may not reflect the actual environmental footprint of chemicals used in the composite I-beam. A breakeven was analysed for this uncertainty. According to the single score results, the cradle-to-grave of the composite I-beam will be equalled to the stainless steel I-beam if the environmental impact of the material stage is increased up to 39 %.

Secondly, the electricity consumption for the manufacturing process of the composite I-beam was obtained from the electricity bills, nominal power consumption and operating hours of the machines. In practice, it is often found that the actual electricity consumption is significantly less than the nominal power consumption. A sensitivity analysis was conducted for this assumption by varying the electricity

**Fig. 6** Contribution percentage of the characteristic results for the cradle-to-grave of the linear metre stainless steel and the composite I-beams



consumption from 100 % (current assumption) to 10 %. Accordingly, the single score values of the cradle-to-grave for the composite I-beam for these alterations are linearly reduced up to 6 %.

Thirdly, the assumptions made for the unavailable electricity mix processes of the suppliers from the selected LCI databases in SimaPro 7.3 software (PRe Consultants BV 2008) may also influence the results as those modified cases were based on the IEA data in year 2008. The LCI databases were the Ecoinvent 2.2 and Australia data 2007. In this instance, the modified cases are compared with the latest IEA data and the CO<sub>2</sub> highlights in 2009 (International Energy Agency 2009; International Energy Agency 2011). Generally, a similar trend of the CO<sub>2</sub> emissions produced by electricity used in those countries is found in both years due to their similar percentages of energy sources. There are some differences in a magnitude of less than 1 % up to 6 % where most countries tend to shift towards the lower environmental impact or renewable energy sources. For example, Australian electricity uses less gas and increases the biofuels and solar while Asia 3 uses more gas than oil in 2009. On the whole, these minor variations of the electricity data source have a minimal impact towards the assessment results.

Finally, the Australian steel recycling rate of 70 % and 30 % was based on the Australian data 2007 database (Grant 2010). A sensitivity analysis was conducted by changed the assumption to 100 % recycling. The single score of the stainless steel I-beam is reduced by 2 % due to the predominantly improvement of the human health damage category which has less impact towards the current results.

## 5 Conclusions and recommendation

Part 1 of this research presents the cradle-to-grave of a linear metre I-beam made from stainless steel (316) and composites. The screening LCA was conducted using the World ReCiPe midpoint and endpoint methods. The life cycle inventory was based on the company provided data and the selected LCI databases. Overall, the single score results reveal that the composite I-beam produces 20 % less than the stainless steel I-beam. The human health damage category has the highest single score at approximately 55 % to 65 %. The main contributor comes from the material stage at a level of 90 % followed by 7 % of the manufacturing process and 3 % of the end of life stages.

According to the cradle-to-gate results, the raw material extraction and the manufacturing stages remain the dominant contributors for both I-beams. However, in the case of the environmental footprint produced by the associated transportation, the composite I-beam case has contributed up to 7 % which is relatively higher than the stainless steel I-beam.

Therefore, the cradle-to-grave results were further by observing their characteristic and normalisation results. The normalisation results showed that one linear metre composite I-beam produces less environmental footprint than that of the stainless steel I-beam in all impact categories. Slightly different trends were found in the characteristic results where the composite I-beam produces less environmental footprint in most impact categories. The exception was found in the climate change, photochemical oxidant formation, terrestrial acidification, marine eutrophication, natural land transformation and fossil depletion impact categories. Thus, the drawbacks of these impact categories will be investigated further in Part 2 in a separate publication which will focus on the effect of different cradle-to-gate scenarios of the I-beams towards the environmental and economic impacts.

**Acknowledgments** The authors are grateful for the input data provided as part of the ‘Composites: Calculating their Embodied Energy’ study funded by the Queensland Government through the Department of Employment, Economic Development and Innovation, and the participant composites companies and institutes.

## References

- Ashby MF (2009) Materials and the environment: eco-informed material choice. Butterworth–Heinemann, Burlington
- Basbagill JP, Lepech MD, Ali SM (2012) Human health impact as a boundary selection criterion in the life cycle assessment of pultruded fiber reinforced polymer composite materials. *J Ind Ecol* 16(2):266–275
- Belboom S, Renzoni R, Verjans B, Léonard A, Germain A (2011) A life cycle assessment of injectable drug primary packaging: comparing the traditional process in glass vials with the closed vial technology (polymer vials). *Int J Life Cycle Assess* 16:159–167
- Bribián IZ, Usón AA, Scarpellini S (2009) Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. *Build Environ* 44(12):2510–2520
- Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build Environ* 46:1133–1140
- Dittenber DB, GangaRao HVS (2011) Critical review of recent publications on use of natural composites in infrastructure. *Compos A Appl Sci Manuf*. doi:10.1016/j.compositesa.2011.11.019
- Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Hirschler R, Hellweg S, Nemecek T, Rebitzer G, Spielmann M (2007) Overview and methodology. Final report ecoinvent data v2.0, No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland
- Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. VROM, The Hague
- Google Map (2012) <http://maps.google.com.au/maps?hl=en&tab=wl>. Accessed 27 March 2012
- Grant T (2010) Australasian SimaPro Database Instructions. Life Cycle Strategies Pty., Ltd., Melbourne
- Hansen K, Zenobia K (2011) Civil engineer's handbook of professional practice

- International Energy Agency (2008) Electricity/Heat in 2008. [www.iea.org/stats/electricitydata.asp?COUNTRY\\_CODE=30](http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=30). Accessed 17 October 2011
- International Energy Agency (2009) Electricity/Heat in 2009. [www.iea.org/stats/electricitydata.asp?COUNTRY\\_CODE=30](http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=30). Accessed 27 March 2012
- International Energy Agency (2010) CO<sub>2</sub> Emissions from Fuel Combustion Highlights, 2010th edn. IEA, Paris
- International Energy Agency (2011) CO<sub>2</sub> Emissions from Fuel Combustion Highlights, 2011th edn. IEA, Paris
- ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework. ISO, Geneva
- Jones CI, McManus MC (2010) Life-cycle assessment of 11 kV electrical overhead lines and underground cables. *J Clean Prod* 18:1464–1477
- Kara S, Manmek S, Herrmann C (2010) Global manufacturing & the embodied energy of products. *CIRP Ann Manuf Technol* 59:29–32
- Khasreen M, Banfill P, Menzies G (2009) Life-cycle assessment and the environmental impact of buildings: a review. *Sustainability* 1(3):674–701
- Kosareo L, Ries R (2007) Comparative environmental life cycle assessment of green roofs. *Build Environ* 42(7):2606–2613
- La Mantia FP, Morreale M (2011) Green composites: a brief review. *Compos A Appl Sci Manuf* 42(6):579–588
- Lawson B (1996) Building materials energy and the environment. The Royal Australian Institute of Architects, Canberra
- Mayyas AT, Qattawi A, Mayyas AR, Omar MA (2012) Life cycle assessment-based selection for a sustainable lightweight body-in-white design. *Energy* 39(1):412–425
- Nebel B, Zimmer B, Wegener G (2006) Life cycle assessment of wood floor coverings. A representative study for the German flooring industry. In *J Life Cycle Assess* 11(3):172–182
- O'Brien-Bernini F (2011) Composites and sustainability—when green becomes golden. *Reinf Plast* 55(6):27–29
- Ortiz O, Castells F, Sonnemann G (2009) Sustainability in the construction industry: a review of recent developments based on LCA. *Constr Build Mater* 23(1):28–39
- Ortiz O, Pasqualino JC, Díez G, Castells F (2010) The environmental impact of the construction phase: an application to composite walls from a life cycle perspective. *Resour Conserv Recycl* 54(11):832–840
- Portworld (2012) <http://www.portworld.com/map/>. Accessed 27 March 2012
- Prasara J, Grant T (2011) Comparative life cycle assessment of uses of rice husk for energy purposes. *Int J Life Cycle Assess* 16:493–502
- PRe Consultants BV (2008) SimaPro 7 User's Manual. PRe Consultants BV, the Netherlands
- Rajendran S, Scelsi L, Hodzic A, Soutis C, Al-Maadeed MA (2012) Environmental impact assessment of composites containing recycled plastics. *Resour Conserv Recycl* 60:131–139
- Ramesh T, Ravi P, Shukla KK (2010) Life cycle energy analysis of buildings: an overview. *Energy Build* 42:1592–1600
- Recipe, Introduction (2011) <http://sites.google.com/site/lciarecipe/project-definition>. Accessed 17 October 2011
- Sharma A, Saxena A, Sethi M, Shree V (2011) Life cycle assessment of buildings: a review. *Renew Sust Energy Rev* 15(1):871–875
- Simitses G, Hodges DH (2005) Fundamentals of structural stability. Butterworth-Heinemann, the United States of America
- Simões CL, Pinto LMC, Bernardo CA (2012) Modelling the environmental performance of composite products: Benchmark with traditional materials. *Mater Des* 39:121–130
- Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. *Compos A Appl Sci Manuf* 40(8):1257–1265
- Tarantini M, Loprieno AD, Porta PL (2011) A life cycle approach to green public procurement of building materials and elements: a case study on windows. *Energy* 36(5):2473–2482
- Torgal FP, Jalali S (2011) Eco-efficient construction and building materials. Springer, London